Single Household Domestic Water Heater Design and Control Utilising PV Energy: the Untapped Energy Storage Solution

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***Abstract*— Photovoltaic (PV) panels and electric domestic water heater with storage (DWH) are widely used in households in many countries. However, DWH should be explored as an energy storage mechanism before batteries when households have excess PV energy. Through a residential case study in Queensland, Australia, this paper presents a new optimized design and control solution to reduce water heating costs by utilizing existing DWH energy storage capacity and increasing PV self-consumption for water heating. The solution is produced by evaluating the case study energy profile and numerically maximizing the use of PV for DWH. A conditional probability matrix for different solar insolation and hot water usage days is developed to test the solution. Compared to other tariffs, this solution shows cost reduction from 20.8% to 63.3%. This new solution could encourage solar households move to a more economical and carbon neutral water heating method.**

***Index Terms*— domestic water heater; photovoltaic systems; self-consumption; energy storage**

I. Introduction

DWH is an energy storage system in households. DWH's performance of supplying hot water is strongly dependent on the size of storage because residential DWHs typically have one low power rating heating element ranging from 1.8 to 3.6kW[1].This heating element operates to recover hot water after consumption. In Queensland Australia, household electric DWHs are frequently connected to utility controlled Tariff 31 ($0.12917/kWh) or Tariff 33 ($0.20299/kWh) [2]. In solar households, however, PV energy in excess of local load is sold to the electricity distributor at the price of feed-in tariff (FIT) which has been reduced from $0.44/kWh in 2012 to $0.06/kWh currently. PV systems are connected to normal mains for which Tariff 11 (T11) is the most common option. Therefore, if PV generation is less than the load, energy is imported from the mains at the T11 price. In Queensland 2014, 53% of households have DWH and 28% of households have PV systems [2]. This research conducts a case study in a household with DWH and PV in Queensland, Australia. The tariff structure used in the study is in Table I.

TABLE I. Case Study Electrical Tariff Structure [3]

Tariff Type	**Tariff 11 (T11)**	**Tariff 31 (T31)**	**Tariff 33 (T33)**	**Feed In Tariff (FIT)**
Name	Standard Residential Tariff (Flat Rate)	Night Rate (Super Economy)	Controlled Supply (Economy)	Solar Feed-in
Available Time	24 hours	Available for a minimum of 8 hours a day;	Available for a minimum of 18 hours a day	PV exceeding domestic loads
Price per kWh [a] ($AUD, including goods and service tax)	0.27916	0.12917	0.20299	0.06

a. Utility daily connection charge is not considered in the case study water heating cost since the connection charge is applied for normal appliances anyway.

DWH is the largest energy consuming appliance using 54% of overall energy imported from the grid in the case study family[4]. For the same case study, PV generation is in excess of household needs and is exported at the price of 6 cents/kWh. Therefore, there is an opportunity to determine if it is more economical to use excess PV energy for DWH energy storage.

The metering configuration impacts the cost analysis of DWH and PV. If only one metering register is available for each metering interval, a positive figure indicates energy import and a negative figure indicates energy export. Under this circumstance, duty ratio control can switch the DWH on and off to match with PV generation so that the metered import kWh is reduced for each metering interval. However duty ratio control cannot reduce metered import kWh when electronic meters use dual registers to accumulatively record electricity import and export energy individually [5]. A dual-

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register electronic meter is installed in the case study household. Therefore, a DWH needs to be designed and controlled suitably to absorb more PV energy for economical water heating.

Photovoltaic self-consumption, solar energy for water heating and energy storage in households are discussed in the following paragraphs.

A. Photovoltaic self-consumption

Equation 1 from [6] is adopted in this study for calculating daily PV self-consumption ratio.

$$\text{PV Self-consumption Ratio} = \text{LL} / \text{TPVG} \tag{1}$$

LL: kWh generated by PV and consumed by local loads during PV available time

TPVG: Total kWh generated by PV

Increasing PV self-consumption for DWH is one form of demand side management. A recent reference [6] states the research gap and its importance in the field: literature on demand side management with PV in a household is limited and this method has great potential for self-consumption. Shifting DWH operation to match with PV generation is discussed in [7] however that study only simulated data for one particular calendar day.

B. Solar energy for water heating

Solar energy for water heating has been researched well. Solar thermal water heaters are highly researched solar technologies. However, it is not popular in Queensland [2], possibly due to its high initial cost, disturbance with housing structure, and the requirement of backup heating mechanism, such as electrical heating, gas or oil boilers [8]. Photovoltaic energy is the alternative energy source for water heating in the case study.

C. Energy storage in households

Extensive research has been conducted on how battery energy storage systems can improve PV self-consumption and reduce power bills [6]. However, due to current high costs of batteries, it is not financially desirable to adopt batteries as the only energy storage option without evaluating other technologies. This study is based on the mature DWH technology with a new research application.

This aim of this research is to provide an optimized water heating power rating design and practical operation time control to reduce water heating costs and maximize PV self-consumption by using existing DWH capacity before considering batteries.

The methodology in Section II describes case study data from energy auditing, new design and control strategy, optimization and conditional probability matrix. Section III presents results for the study. Section IV discusses the costs implication compared to other tariffs.

II. METHODOLOGY

This section describes the methodology used in the research. The case study, new power rating and control strategy, MATLAB optimization and conditional probability matrix are described in sequence.

A. Case Study

Electricity is the only energy source in the household. The household is occupied by a family of 2 adults (full time work) and 3 school aged children. The PV system consists of 6kW of PV panels with a 5kW inverter. With a 315 liter storage tank and 3.6kW rated element, the DWH is the largest power rated appliance and the largest single consumer of electricity. In operation its single heating element works at full power rating. It cannot vary power to seize the most of the PV energy because an average PV generation profile is a bell shape, increasing in the morning from zero to the peak around noon then decreasing to zero near to dusk [9]. The PV generation profile's symmetrical axis is around the noon time which coincides with solar radiation peak time [10]. In the case study, all electrical circuits and the PV generation are metered by a Home Energy Management System. These recorded data are used as the base for this study.

Any solution to match DWH with PV needs to be easy and cost effective to build and maintain. Modifying the DWH to include as many heating elements as needed to match with PV generation is infeasible. Controlling the DWH via frequently switching on and off the heating elements to match with PV profile is also impractical, due to the limited number of switching actions in the life expectancy of electrical devices. Therefore, a new design is introduced in the next section.

B. New Design and Control Strategy

Through engineering design, a new power rating and operation time control of a two-element DWH giving three power ratings is introduced. The first power rating comes from the main heating element with a lower rating; the second rating is by the booster heating element with a higher rating; the combination of the two elements provides the third power rating. The following control is proposed, however, the times to start and power ratings are subject to the optimization in the next section and results in Fig. 1.

1) Operation Interval for the 1st Rating

T1-1 in Fig. 1:

- Starts when measured Net Energy Profile (NEP, refer to next section for definition) is larger than the 1st rating or the optimized start time from next section, whichever occurs first.
- Ends when the 2nd rating starts

T1-2 in Fig. 1:

- Starts again when the 2nd rating ends
- Ends until the required energy is consumed

2) Operation Interval for the 2nd Rating

T2-1 in Fig. 1:

- Starts when measured NEP is larger than the 2nd rating or the time from optimization, whichever occurs first. Or the 2nd rating need not start if the 1st rating can provide the required energy.

- Ends if the 3rd rating starts.

T2-2 in Fig. 1:

- Starts again when the 3rd rating ends
- Ends until the balance of the required energy is met.

3) Operation Interval for the 3rd Rating

T3 in Fig. 1:

- Starts when measured NEP is larger than the 3rd rating. Or the 3rd rating need not start if the 1st and 2nd ratings operation can provide the required energy.
- Ends at mirrored time of the starting time by the mid-day (e.g. 11am to start -> 1pm to end)
- Ends 1 hour later if the start time is after mid-day

The required energy to heat up water is calculated from water specific heat capacity timed by the temperature difference between temperature setting and temperature measured inside DWH in the morning before the 1st rating start time. When attempting to use daytime PV, the DWH's electricity supply is cut off overnight and the water temperature in the DWH decreases below the temperature setting due to usage and loss of heat overnight. Thermostat control and stratification due to buoyancy effect are neglected in this study, as is the possible benefit of adding insulation to the storage tank.

C. Optimisation

Polynomial linear least square fit curve (PLLSF) of net energy profile (NEP) is used in the power rating and operation time optimization. The net energy profile at any time *i* is calculated by (2) which is extended to 24-hour time domain from Eq. (1) in [8].

$$\text{NEP (i)} = \text{Generation (i)} - \text{Consumption (i)} \quad (2)$$

If NEP is positive, there is more PV generation than electricity consumption and the NEP amount is sold at the FIT rate. Otherwise, there is less PV generation than electricity consumption and the NEP amount is bought at T11. A 5-minute interval is used for calculating the energy profile based on case recorded data (24 hours = 288 of 5 minutes).

There is no air conditioner in the household and during valuable PV generation time (8am to 4pm), other appliances (e.g. cooking appliances) work intermittently without consuming large amount of energy. Therefore, from 8am to 4pm the shape of net energy profile depends on the solar generation profile. The small variation between weekdays and weekends is neglected in the study.

Two weeks of site recorded data at 5-minute intervals are averaged to generate a 24-hour PLLSF energy profile. These data include all loads and PV generation except DWH, from 3 to 10 March and 2 to 8 June 2015. These two weeks are selected because their mean weather and solar insolation parameters are similar to the case study yearly mean records [11-13].

MATLAB *fmincon* function is used to optimize DWH power rating design and operation time. In the optimization process, variables include three power ratings and the operation interval of each rating during positive NEP periods. DWH ratings and operation intervals will construct the rectangular areas representing the energy available for water heating. The rectangular areas need to be constrained within the PLLSF energy profile. The objective of the optimization is to maximize the stepped rectangular areas under the PLLSF energy profile. Results are shown in Fig. 1.

D. Conditional probability matrix

A conditional probability matrix (CPM) is developed based on case solar insolation (SI) and hot water usage to test the new optimized design and control solution.

SI is one of the most significant variables influencing PV energy output (0.91 Pearson Correlation Coefficient for the case[14]), so it is important to classify SI days in each season corresponding to certain hot water usage. SPSS Two-Step Clustering technique with sequential clustering approach and agglomerative hierarchical clustering method [15] is used to automatically determine the clusters of SI days: two types of SI days in summer and autumn, three types of SI days in spring and winter. The SI data are obtained from NASA [16]. The SI day type's probability matrix is presented in Table II. Ten individual days of site recorded data are used to examine the costs and PV self-consumption ratio for the optimized DWH design and control. These ten days SI observation data match with the ten SI day types' values with 1.7% mean absolute percentage error. Three hot water usage day types are identified for each season with the same tool based on onsite monitoring and historical bills. Seasonal DWH heating energy per day and in-season variations are presented in Table III. The CPM is generated by associating each seasonal SI day probability with each hot water usage day probability and presented in Fig. 2.

TABLE II. SOLAR INSOLATION DAY TYPES PROBABILITY MATRIX

Seasons	Day Types	kWh/m2/Day [a]	Probability [b]
Spring	1	5.8	41.80%
	2	6.3	48.40%
	3	7.1	9.90%
Summer	4	5.7	53.85%
	5	6.8	46.15%
Autumn	6	3.6	58.95%
	7	4.8	41.05%
Winter	8	3.4	24.30%
	9	4.1	39.20%
	10	4.9	36.50%

a. *kWh/m2/day is the mean solar insolation data of each cluster*
b. *Distribution of day types in each season.*

TABLE III. DAILY ENERGY REQUIRED FOR DWH

Seasons	Seasonal Mean DWH kWh/Day	High Usage (HU) kWh/Day	Mid Usage (MU) kWh/Day	Low Usage (LU) kWh/Day
		21.51%	54.84%	23.66%
Spring	8.97	13.61	9.40	3.75
Summer	6.81	10.33	7.14	2.85
Autumn	12.46	18.9	13.06	5.21
Winter	17.01	25.80	17.83	7.11

III. RESULTS

This section presents the results of the optimized DWH design and operation for the case study, CPM, water heating costs under each SI and hot water usage day type and combined water heating costs with CPM.

The optimized heating elements ratings are: 0.8kW, 1.8kW; the combined rating is: 2.6kW. The 1st rating starts latest from 9am and the 2nd rating starts latest from 10am. Fig. 1 provides the DWH operation cycles with the optimized ratings in an average NEP described in Methodology – Optimization.

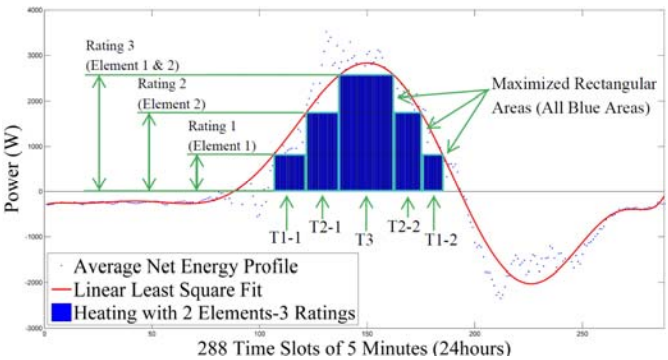

Figure 1. DWH optimized design and Average NEP

Fig.2 presents the conditional probabilities for SI and hot water usage day types. The horizontal axis is for SI day types and hot water usages types are on the vertical axis. High probabilities are in mid usage range across all SI day types.

Fig. 3 presents the water heating costs for all individual types with this new solution. These costs include occasional purchase electricity from T11 in case of insufficient PV energy and the opportunity cost of not selling the PV energy used for DWH energy storage. Mid to high hot water usages during winter days attract the most water heating costs.

Fig.4 shows the costs for all individual types associated with CPM in a year. High costs occur in mid hot water usage of autumn and winter type days, mostly because mid hot usage days are the most prevalent day types and days in autumn and winter have less PV generation than other seasons.

Fig. 5 shows the percentage of PV self-consumption into DWH. High percentages occur mostly on autumn and winter mid to high water usage days.

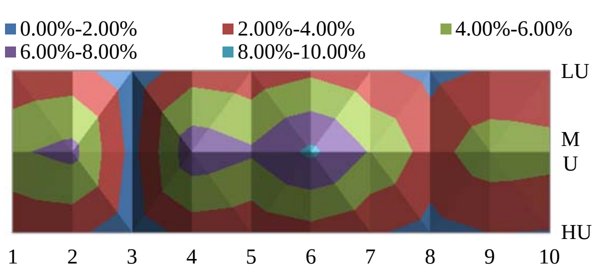

Figure 2. Conditional Probability for Usage and Day Types

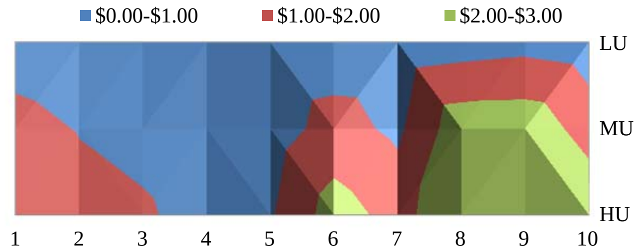

Figure 3. Water Heating Costs for Individual Usage and Day Types

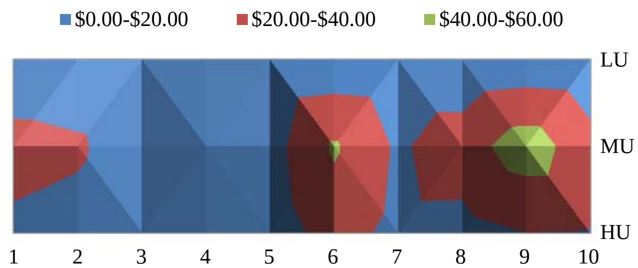

Figure 4. Water Heating Costs for Individual Usage and Day Types with Conditional Probability in a year

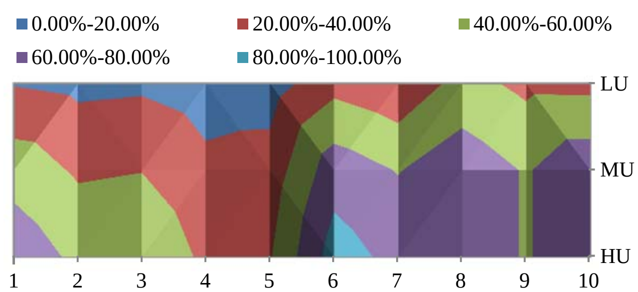

Figure 5. Percentage of PV Self-consuption into DWH Storage

Table IV compares the water heating cost of this solution with T11, T33 and T31 supply.

TABLE IV. COST COMPARISION AMONG TARIFFS

	Tariff 11 **T11**	**Tariff 33** **T33**	**Tariff 31** **T31**	**This Solution**
Yearly Costs [a]	$1,149.18	$835.64	$531.75	$421.30

a. Calculation is based on a year recorded 4116.56 kWh for water heating.

Compared to T11, T33 and T31, this solution shows cost reduction of 63.3%, 49.6% and 20.8% respectively.

IV. Discussion

This section attempts to analyze the costs and benefits of the new DWH design and control solution. The major finding of this study is that the new DWH design and control is cost effective across different SI and water usage days. The results also demonstrate that the solution is resilient during adverse days of low SI due to cloud or rainy days because the new rating has lower power ratings to use less normal mains and use as much PV as possible.

Net present value analysis (NPV) is presented for the DWH expected 10-year life in Table V, considering $480 of retrofitting cost for the solution (including labor and material). The yearly positive cash flow is calculated from savings compared to super economy T31. At the end of DWH's 10 years expected life, its NPV is positive of $486.91. Positive cash flow can be realized after 4 years of implementation.

TABLE V. Net Present Value Analysis

Year	Yearly Cash Flow	Accumulative Cash Flow
0	-480.00	-480.00
1	107.78	-372.22
2	105.15	-267.07
3	102.59	-164.49
4	100.09	-64.40
5	97.65	33.24
6	95.27	128.51
7	92.94	221.45
8	90.68	312.13
9	88.47	400.60
10	86.31	486.91
Net Present Value [a & b]	486.91	

a. *Discount rate in the analysis is assumed to be 2.5% in line with Reserve Bank of Australia medium term target [17].*

b. *Inflation rate for electricity tariff is assumed to be 6.93%, based on average Queensland tariff increase 2010-2015 [18].*

The presented solution is practical, easy to build and maintain, and it can be beneficial to all households with comparably large PV systems. However, its accrued benefits will be limited for families in low SI climate areas.

V. Conclusion

This research provides a feasible, reliable and more accessible solution to store energy for families and communities compared to battery energy storage systems. The solution can effectively reduce power bills for families by maximizing local sustainable and carbon neutral PV energy into water heating. This research is a part of an ongoing Australian Research Council Linkage project. Future work includes PV system sizing impact onto the water heating cost and dynamic modelling of DWH temperature.

Acknowledgment

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